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THERMAL ANALYSIS AND DEVELOPMENT OF A THAWING PROCEDURE FOR FROZEN FOOD PACKAGES

by
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14. ABSTRACT
Currently there are no field provisions for thawing in accordance with military doctrine to prevent the proliferation of illness-causing microbes. The current study is aimed at investigating the thermodynamic realities behind possible thawing procedures. Thawing of meat under field conditions was simulated and evaluated through mathematical models and experimental testing. Input variables and accountability factors included initial product temperatures, thermal characteristics of the packaging, and air circulation. It was verified that external temperature, packaging properties, and outside heat transfer coefficients were factors having the greatest effect on the process. Tests show the existence of air pockets within meat packaging is extremely effective in reducing thawing time.

15. SUBJECT TERMS

THAWING	FIELD FEEDING	FOOD SAFETY	FOODBORNE ILLNESS
FROZEN FOODS	MEAT	FOOD PREPARATION	FROZEN MEATS
BACTERIA	THERMAL ANALYSIS	FOOD STORAGE	

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Preface

Changes to field food storage and handling equipment were prompted by doctrine calling for increased serving of fresh perishable rations in-theatre. Since most fresh ration meat is stored frozen, it must be thawed to permit handling, control meal quality, and ensure complete cooking. It is important to thaw foods correctly to avoid the proliferation of bacteria or viruses, and so protect against illness. Currently there is no way for cooks operating in the field to properly thaw meat in the ways mandated by documents FM 10-23 and TB MED 530.

This report begins study of the problem by modeling the thawing process and verifying the model with experimental testing. Results from testing during the summer of 2001 will be used to support subsequent research efforts involving development of thawing equipment and procedures. At the writing of this report, a Small Business Innovative Research (SBIR) project, *Isothermal Blanket for Safely Thawing Frozen Foods,* is in the works.

The study was performed by the Rochester Institute of Technology (RIT) Mechanical Engineering Department under the auspices of a Natick Soldier Center Combat Feeding Program, Broad Agency Announcement objective. It was conducted through U.S. Army contract #DAAD16-01-P-0253 and supports development of equipment to provide thawing equipment suitable to Rapid Deployment Food Service for Force Projection.

Some of the experiments were conducted at RIT by students as part of their coursework in heat transfer. Grappling with this thermal engineering problem provided them with valuable practical experience in data acquisition systems, engineering modeling, and real world technical exploration.

Acknowledgements

Special thanks goes to the students of the Heat Transfer II course held at the Rochester Institute of Technology. In particular, the dedicated efforts of Mark Steinke, a graduate student in the Thermal Analysis Lab at RIT, are acknowledged. The support of personnel at the U.S. Army Natick Soldier System Center, and from the Mechanical Engineering Department at the Rochester Institute of Technology, is appreciated.

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Executive Summary

The proper thawing of frozen meat is important to maintaining food safety during field-feeding operations. Current practice is to leave cases of frozen meat overnight, in the open, to thaw at ambient temperatures. With no safety measures, or controls over the process, the meat may not thaw completely by meal time, or its outer layers thaw early, reach temperatures above 41°F for extended periods of time, and subsequently breed unsafe levels of bacteria and viruses.

The current study is aimed at investigating the thermodynamic realities behind this thawing procedure such that the behavior and event sequence are well understood. This knowledge will lead to development of equipment and strategies cooks can use to mitigate any danger.

Thawing of meat under field conditions was simulated and evaluated through mathematical models and experimental testing. The major variables sought were thawing time, maximum temperature attained in the meat, and the duration any portion of the meat was above 41°F.

The numerical model used to simulate the thawing process was developed within an Excel spreadsheet using finite difference equations. Equations were derived assuming nodes placed at various depths in the meat. Input variables and accountability factors included initial product temperatures, thermal characteristics of the packaging, and air circulation. The numerical results matched experimental findings to within ±10 percent.

During subsequent experimental testing, full cases of various meats were exposed to ambient conditions maintained at temperatures from 35 to 77°F. The results indicate thawing times range from 12 to 36 hours. The maximum duration outer meat surfaces were above 41°F ranged from 5 to 10 hours when thawing in 72°F air.

It was determined that external temperature, packaging properties, and outside heat transfer coefficients were factors having the greatest effect on the process. Therefore, design of a satisfactory thawing system, one that will thaw food in a reasonable amount of time within maximum allowable temperature limits, will involve careful consideration of these variables.

The most promising tactic evaluated that would provide safe and rapid thawing, was air circulation with a controlled heat transfer coefficient.

Furthermore, tests comparing tightly packed hamburgers and steaks with loosely packed sausages or chicken show that the existence of air pockets within the meat packaging was found to be extremely effective in reducing thawing time because convection inside the food packaging transports heat quickly from the surface of the plastic bags to the interior meat pieces.

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THERMAL ANALYSIS AND DEVELOPMENT OF A THAWING PROCEDURE FOR FROZEN FOOD PACKAGES

1. Summary

Generally, fresh/perishable food ingredients result in better tasting and more nutritious meals. This improves soldier moral and physical performance. Consequently, Army doctrine has been changed to increase the number of cook-prepared fresh-food meals served in-theatre. This requires storing and transporting meat in frozen condition, and subsequently thawing it once it has been delivered to deployed field kitchens.

The refrigerated containers at ration break points and supply depots hold the product at temperatures of 0°F or lower. After delivery to field units, boxes of meat are typically kept on their pallets or separated as necessary, then left in the open to thaw, despite doctrine mandates which require thawing in ways that prevent bacteria growth. It is reported that food remains this way for 12-18 hours, possibly in a tent, to thaw at ambient temperatures as high as 105°F, because food service personnel have no alternative and proper recourse for safe thawing. The result is that the meat may reach excessive temperatures (i.e., anything above 41°F), for extended periods of time.

This project sought to identify not only the thermodynamic realities surrounding these current thawing practices, but also to apply this experience to analyzing some simple, initial, concept solutions. The approach involved development of a mathematical model that can provide greater theoretical understanding, and allow for rapid and inexpensive simulation of a variety of conditions. The numerical model used to simulate the thawing process was developed using Excel and based on finite difference equations. Equations were derived assuming nodes located at various depths in the meat. Model predictions were backed up by generating experimental data to illuminate any issues, mainly gaining insight into approximate thawing times for a limited number of configurations.

Initial experiments were conducted using a small quantity of hamburger patties surrounded by insulation to simulate conditions at the center of a box of meat. At an ambient temperature of 75°F, the patties remained unthawed even after 30 hours. Applying forced convection with a fan decreased thawing time to roughly 15 hours. For this test, the heat transfer coefficient was around $17 W/m^2 °C$. These experiments confirmed the results predicted by the numerical model.

Additional experiments were conducted using genuine boxes of meat from the UGR-A. Tested were steak, chicken, and sausages. The meats were first thawed in a refrigerated environment controlled at 35°F and 45°F, then at 75°F. A second test at 75°F was performed with forced convection applied. At an ambient temperature of 35°F, complete thawing did not occur. Raising the temperature to 45°F provided a satisfactory thawing of all meat products.

Naturally, thawing at 35°F took far longer than would be practical in field situations. The actual thawing time is unknown, since the test was cut short. It did however provide data at the extreme range of possible conditions, and could be useful for evaluating different ways of handling frozen product. For instance, transportation of the meat at this relatively elevated

temperature may be a way to simultaneously reduce logistical costs while providing some prethawing prior to arrival at the feeding site.

Thawing of meat in an ambient temperature of 75°F without any forced convection resulted in unsatisfactory thawing because the temperature of the outer layer of the meat was well above the 41°F limit for several hours, reaching as high as 55°F before the interior thawed. It was discovered this situation could only be avoided with ambient temperatures controlled at 45°F, with air circulation provided to reduce the thawing time.

The packaging density was found to be a significant variable. That closely stacked hamburger patties could not be thawed even after 30 hours offered a premonition of this. But when full cases of meat were thawed the results could be compared. The chicken and sausage, which were very loosely packaged, exhibited much faster thawing times than the steak which was very tightly arranged. Furthermore, the temperature uniformity was better with the chicken and sausage. It is believed air gaps surrounding the meat allow for good circulation and enhance convention from the interior of the box.

Further research is recommended. It would be useful to examine several variables in greater detail. These would include: packaging density, air velocity, and box layouts. The performance of a complete set of frozen items from the UGR-A thawed simultaneously within an enclosure will of course be different than the individual cases tested in the present work. This work would then be followed by system level simulation covering details of an entire system.

2. Introduction

2.1 Background

Generally, fresh/perishable food ingredients result in better tasting and more nutritious meals. This improves soldier moral and physical performance. Consequently, Army doctrine has been changed to increase the number of cook-prepared fresh-food meals served in-theatre. Naturally, this has affected the ways food is handled to protect against food spoilage, product loss, and, most importantly, food-borne illness from salmonella, *Escherichia coli*, *staphylococcus*, and other bacteriological and viral microbes. Although there are no documented statistics to highlight the extent of food-borne illness amongst the military population, it is recognized that most cases go unreported, and the situation can lead to grave consequences.

2.1.1 Fresh Food in Field Feeding

The palletized Fresh/Perishable Unified Group Ration (UGR-A) appears to be the direction food distribution is heading. Of particular concern are the meat and eggs included with the meals, and in general, the importance of tempering applies only to these products. Meats included are turkey, ham patties, bacon, pork ribs, pork chops, hamburger patties, and Swiss steak. Characteristics for some items are shown in **Table 1.** The meat is wrapped with plastic in a variety of configurations, and layered in cardboard boxes. The basic configuration is shown in **Figure 1**. A large variable is the packing density. Some meat, such as the hamburger and steak, is arranged in slabs with little or no air between individual portions. Chicken and sausages are packaged much more loosely, probably because of their irregular shape.

Table 1. Description of UGR-A Packaged Meat

Meat	Dimensions	Description
Turkey	13 ½ x 11 x 6	cardboard box containing 6, 2 lb patties in plastic bags
Ham	15 ¼ x 11 x 4 ¼	cardboard box containing 12 plastic bags at a total weight of 11.25 lb
Pork Ribs	14 x 11 x 6 ½	cardboard box containing 14 lbs in plastic bags
Steak	17 x 10 x 7	cardboard box containing 22 lbs in a plastic bag
Chicken	17 ½ x 11 ½ x 4 ½	cardboard box containing 10 lbs in a plastic bag
Sausage	16 x 10 ½ x 5	cardboard box containing 10 lbs in a plastic bag

Note: The steak, chicken, and sausage were products tested in this study.

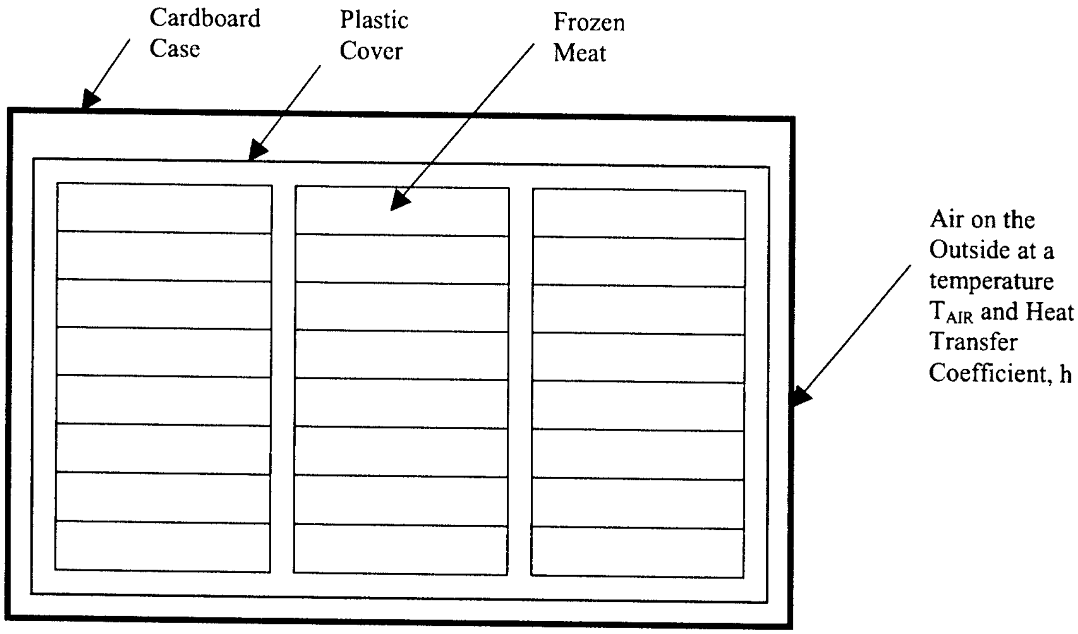

Figure 1. Schematic of Typical UGR-A Frozen Meat Packaging

2.1.2 Food Handling

The best way to protect large quantities of fresh food for long term storage and transportation, is to freeze it, and the frozen portions of each UGR-A are grouped together on pallets for this purpose, ever ready for deployment. The refrigerated containers at ration break points and supply depots hold the product at temperatures of 0°F or lower (the shelf life specification is given for 0°F).

Both the unrefrigerated and frozen components are transported and delivered to the field kitchen units during late afternoon. When the food arrives on site, it must be thawed to permit handling, prevent cooked meat from having a raw center and overcooked exterior, and allow cooks to control final product quality. In general, all meat products except the hamburger will require thawing prior to cooking. The bags of scrambled eggs will also require thawing.

The cases are typically kept on the pallet or separated as necessary, and despite doctrine mandates, left in the open (if the temperatures are above freezing) to thaw. It is reported that food remains this way for 12-18 hours, possibly in a tent, to thaw at ambient temperatures as high as 105°F, because food service personnel have no other recourse.

Cooks generally find that thawing to 28-30°F with some ice crystal still visible will permit handling and provide a margin of safety while resulting in a mostly quality meal. But this is an uncontrolled procedure; even if some parts are frozen, others can reach unsafe temperatures, which is why such practices are in violation of the basic doctrine for field feeding, FM 10-23, that requires tempering to be performed in a 45°F refrigerator.

2.1.3 Logistics

A typical field-feeding schedule is that 250-500 troops will be fed cook-prepared meals for breakfast and supper, on a daily basis. Lunch is MREs (Meal, Ready to Eat) which require no refrigeration, cooking, or other kitchen services.

Food is delivered on a 2-2-3 weekly schedule (e.g. Monday, Wednesday, Friday). Therefore, if food were to take one day to thaw, it might be necessary to be managing 750 portions at any one time. Garrison cooks will often begin the thawing process two days ahead of a meal, but field cooks may not have this much time since the unpredictability of maneuvers limit advanced planning. Furthermore, with delivery three times per week, these are three times there may not be enough time to prepare before the day's meals. It is estimated cooks will prefer having an entire day's meat supply thawed by morning, so depending on what time the food is delivered the previous day, this could limit availability to as little as 16 hours, but it is anticipated 18 hours is reasonable.

Though all fresh food in the field requires refrigeration in any case, it is not practical to provide electricity for this equipment via 24 hour generator support. Studies of how kitchens are used show that generators would be used only during mealtimes. This amounts to five hours each morning and five hours each evening, with four hours of downtime at midday and ten hours downtime overnight during which there is no power. These factors will influence thawing procedures and the equipment required.

2.2 Project Scope

This project heralds the beginning of problem study. The experimental work will help in quantifying the problem, and numerical models will illuminate the specific effects of various parameters affecting the thawing process. The major variables sought were thawing time, maximum temperature attained in the meat, and the duration any portion of the meat was above 41°F.

The project seeks to identify not only the thermodynamic realities surrounding the current thawing process, but also to apply this experience to analysis of some simple, initial, concept solutions. The resulting picture will help define the extent of safety issues and serve to influence future designs of equipment suitable to assisting cooks perform thawing safely and predictably. It is anticipated further research will focus on defining size, weight, and power requirements of various imagined solutions.

The numerical model used to simulate the thawing process was developed within an Excel spreadsheet using finite difference equations. Equations were derived assuming nodes placed in the air stream, on the surface of the case/packaging, and in the meat. Input variables and accountability factors included initial product temperatures, thermal characteristics of the packaging, and air circulation.

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3. Numerical Analysis

3.1 Baseline Experimentation

Before beginning construction of the mathematical model, a simple test was carried out with a stack of 9, ¼ pound beef patties to gain a rough understanding of behavior and thawing times for model verification. The stack was wrapped on four sides with insulation and plastic wrap. This simplified analysis to 1-dimensional conduction, with variables due to air gaps and packaging eliminated. Thermocouples were inserted at locations intended as nodes for the numerical model. They were wired to a computer equipped with data acquisition hardware and LabVIEW® instrument management and data logging software. Data was collected at thirty second intervals. Initial temperature of the meat was -8°F (-22°C) and ambient temperature was 72°F (22°C). Two experimental runs were conducted

Figure 2 shows the transient temperatures at various nodes. In the trials, thawing at the center node was attained after 12-18 hours. Temperature of the plastic wrapping rose quickly because it has little thermal mass and is in direct contact with ambient temperatures. Naturally, it took longer for temperatures inside to rise from -8°F (-22°C) to about 32°F (0°C) because it takes longer for ambient warmth to conduct inward from the surface. As any given node reached 32°F (0°C), it temporarily plateaued as the water transitioned from ice to liquid, then continued to rise once latent heat requirements were met. This plateau heavily influences the thawing process because adjacent nodes toward the interior are exposed to limited thermal potential.

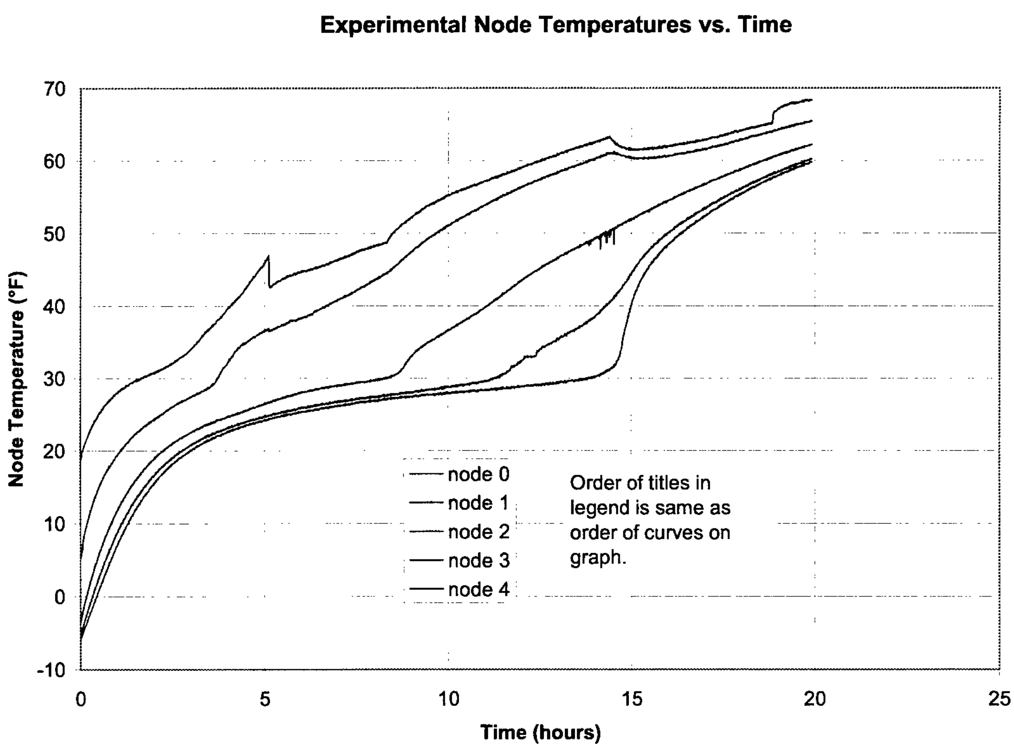

Figure 2. Experimental Thawing of Beef Patties in T_{amb}=72°F (22°C)

Figure 2 also illustrates well why there is concern about uncontrolled thawing at ambient temperatures: most of the temperature locations near the surface of the pile were above the safe limit of 41°F (5°C) for more than four hours. The outer node temperature reached almost 64.4°F (18°C) by the time the center thawed, and was above 41°F for over 9 hours making it a breeding ground for microorganisms. There are two fundamental solutions. One is to speed internal thawing to shorten the time external nodes are too warm, the other is to thaw in ambient air of 41-45°F (5-7°C) or lower as recommended by the FM 10-23.

To test this later possibility, the -8°F (-22°C) hamburger was thawed at an ambient temperature of 41°F. The outer node reached a temperature close to 41°F and of course remained so for the entire duration of the thawing process. That the meat took over 35 hours to completely thaw is a major drawback to this approach, as this is well over the desired limit of 16-18 hours based on operational considerations of field kitchen units. However, as we shall see later, this beef patty configuration is not representative of actual product thawing, only the numerical model.

3.2 Model Development

The experimental results presented in the last section were obtained for specific conditions. To perform material simulations across an entire matrix of variables including ambient temperature, wind velocity, and initial meat temperature would be prohibitively costly and time consuming. So, for looking at various thawing options, it is valuable to have a tool that can predict the transient thermal performance of any process as conditions vary. Furthermore, the exercise of developing a model capable of predicting thawing time and node temperatures can provide great insight. Consequently, a numerical model using the finite difference method was created within a Microsoft Excel spreadsheet.

3.2.1 Assumptions

Accurate modeling of the thawing process is difficult due to complexity of parameters and their relationships. The most elusive key parameters, include:

- outside heat transfer coefficient between the casing and the ambient air
- shape and effect of air gap between the casing and the plastic wrap
- shape and effect of air gap between the plastic wrap and the meat
- shape and effect of air spaces between pieces of meat

The major assumptions influencing the modeling problem are:

- The package of meat is modeled as a block of solid ice of identical dimensions. Future models may wish to refine this assumption.
- The meat is insulated on four sides and the heat transfer is assumed to be one-dimensional. The center plane between the un-insulated top and bottom surfaces is considered to be insulated. Therefore, only one side of the center plane needs to be evaluated. This assumption is valid since the case can be broken down into four symmetrical elements. However, it is recognized that due to their symmetrical nature hamburgers may have less exposed surface area when packaged compared to chicken.
- The initial convection coefficient, h, is assumed to be 10 W/m^2*K.

Details of developing the finite difference scheme are described as follows:

- The block of ice is broken down into five nodes. The surface and center nodes are half nodes, the rest are full nodes.
- A forward-difference, explicit, method is used.
- The Fourier number is kept under ½. This is a simple test of convergence for the finite difference method, which is the method used to calculate temperature values at all nodes with respect to time.
- Each node will go through two types of heating phases, sensible and latent. Initially, the node will go through a sensible phase until it reaches a temperature of 32°F (0°C). Once it reaches this temperature the latent phase begins. A surface node will reach the latent phase first followed by its immediate neighbor. The insulated center node will be the last. The surface node must completely finish its latent phase before the node next to it can start its latent phase. This is the case for all nodes. Once a node passes through latent heating it returns to sensible temperature change.
- The properties of water and ice differ sufficiently. During sensible heating of a node from 8.3°F (–22.4°C) to 32°F (0°C) use the properties of ice. During the latent phase of a node use the average value between ice and water properties. Once the node has thawed completely, use the properties of water.

3.2.2 Description

The model was designed to be flexible; variables in the spreadsheet can be changed to modify boundary conditions and reflect characteristics of the meat, packaging, or environment. Output is the tracking of temperatures at several locations within a case of frozen meat as it thaws. Thermocouple locations were chosen to correspond with nodes used in the numerical model. The nodes to be tracked (also illustrated in **Figure 3**) were defined as follows:

- Node 0 – on outside of plastic cover
- Node 1 – 12 mm inside meat
- Node 2 – 37 mm inside meat
- Node 3 – 62 mm inside meat
- Node 4 – 87 mm inside meat

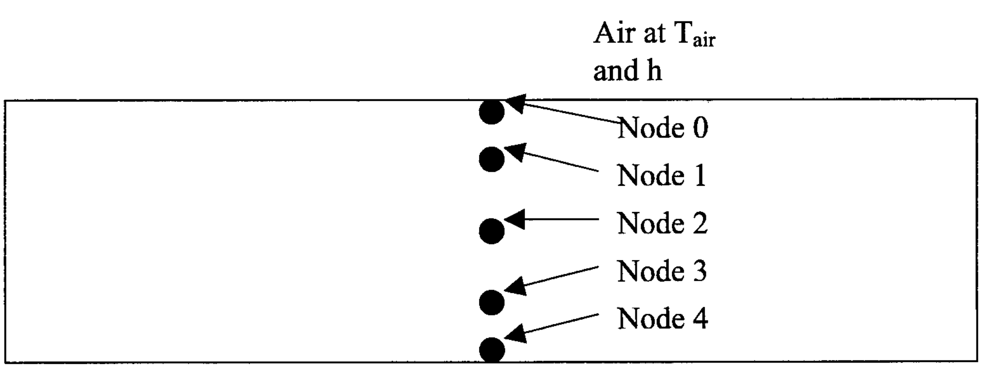

Figure 3. Schematic of Nodes used for Finite Difference Representation

3.2.3 Analytic Expressions

Nomenclature (with known values)

h = convection coefficient = 10 W/m^2*K (initial guess)

Δy = distance between nodes = 0.00833 meters

$\Delta \tau$ = time increment = 26.5 seconds

T_∞ = air temperature = 5°C or 25°C

ρ_{ice} = density of ice = 920 kg/m^3

ρ_{water} = density of water = 1000 kg/m^3

$\rho_{mixture}$ = density of ice/water mixture = 960 kg/m^3

k_{ice} = thermal conductivity of ice = 1.955 W/m-K

k_{water} = thermal conductivity of water = 0.574 W/m-K

$k_{mixture}$ = thermal conductivity of mixture = 1.26 W/m-K

Cp_{ice} = specific heat of ice = 2040 kJ/kg-K

Cp_{water} = specific heat of water = 4211 kJ/kg-K

L = latent heat of melting for ice = 333 kJ/kg

p = time step, integer

T_m^p = temperature of node m at time step p (°C)

Equations

- The surface node is to be modeled differently than all other nodes since it has convection at one surface. The surface node temperature is calculated using equation **(1)**.

$$T_m^{p+1} = T_m^p + \frac{h*(T_\infty - T_m^p)*\Delta\tau}{\rho*\Delta y*Cp} - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\rho*\Delta y^2*Cp} \quad \textbf{(1)}$$

- The energy of the surface node is needed to find out when the node changes phases. Equations **(2)** and **(3)** are used at the surface node to calculate energy accumulation.

Sensible: $$h*(T_\infty - T_m^p)*\Delta\tau - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\Delta y} = \rho*\Delta y*Cp*(T_m^{p+1} - T_m^p) \quad \textbf{(2)}$$

Latent: $$h*(T_\infty - T_m^p)*\Delta\tau - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\Delta y} = \rho*\Delta y*L \quad \textbf{(3)}$$

The right sides of the two previous equations can be solved for in joules per unit-area, knowing the density, section width, specific heat, temperature difference and latent heat of fusion. For both these equations, when the sum of the left side (stored energy per unit-flux-area over time) equals the prescribed value on the right side a switch takes place from either sensible phase to latent phase or vice versa. Once a node switches from latent heating back to sensible, the energy equations are of no concern anymore.

- The interior nodes are based solely on conduction between nodes. The temperature is calculated at the interior nodes using equation **(4)**.

$$T_m^{p+1} = T_m^p + \frac{k*(T_{m-1} - T_m^p)*\Delta\tau}{\rho*\Delta y^2 * Cp} - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\rho*\Delta y^2 * Cp} \quad \textbf{(4)}$$

- The energy of the interior nodes is used for the same reasons as the surface node, and the equations are similar. Equations **(5)** and **(6)** are used to compute the energy accumulations at the interior nodes.

Sensible: $$\frac{k*(T_{m-1}^p - T_m^p)*\Delta\tau}{\Delta y} - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\Delta y} = \rho*\Delta y*Cp*(T_m^{p+1} - T_m^p) \quad \textbf{(5)}$$

Latent: $$\frac{k*(T_{m-1}^p - T_m^p)*\Delta\tau}{\Delta y} - \frac{k*(T_m^p - T_{m+1}^p)*\Delta\tau}{\Delta y} = \rho*\Delta y*L \quad \textbf{(6)}$$

- Since the center node is insulated, it does not have a node after it for evaluation; it is therefore necessary to use the backwards difference method. The equation used to compute the temperature at the insulated center node is given in equation **(7)**.

$$T_m^{p+1} = T_{m-1}^p + \frac{k*(T_{m-1} - T_m^p)*\Delta\tau}{\rho*\Delta y^2 * Cp} \quad \textbf{(7)}$$

- The energy of the insulated center node uses the equations **(8)** and **(9)**, which are to be evaluated identical to the other nodes.

Sensible: $$\frac{k * (T_{m-1}^{p} - T_{m}^{p}) * \Delta\tau}{\Delta y} = \rho * \Delta y * Cp * (T_{m}^{p+1} - T_{m}^{p}) \quad \textbf{(8)}$$

Latent: $$\frac{k * (T_{m-1}^{p} - T_{m}^{p}) * \Delta\tau}{\Delta y} = \rho * \Delta y * L \quad \textbf{(9)}$$

- Since the surface and insulated center nodes are both half nodes, considerations are made when calculating their energy equations. The values on the right hand side of the equation are divided by two, which correctly illustrates that half the energy is needed compared to the interior nodes, which are full nodes.

3.3 Results

The completed mathematical model was used to predict thawing of the beef patties at an ambient temperature of 72°F (22°C) with an initial temperature of -8°F. As can be seen from the graphical results in **Figure 4**, the model predicts the core takes 25 hours to thaw.

This is 10 hours longer than that shown in **Figure 2**. The primary unknown is the heat transfer coefficient. The assumed ambient heat transfer coefficient can be increased until the results of the model and actual experiment match. The heat transfer coefficient was assumed to be 10 W/m^2K for this run. Though most other conditions are identical, recall that the experimental study was conducted on meat not in the original cardboard container, while the model accounts for this additional variable.

Figure 5 shows the results of the numerical model with an outside heat transfer coefficient value of 17 W/m^2K. Thawing time was 18 hours. **Table 2** shows the results of **Figure 4** and **Figure 5** in tabular form. Using a value of 25 W/m^2K resulted in a thawing time of approximately 15 hours, closely matching the experimental value of 14.6 hours.

It is anticipated that moisture migration due to repetitive freeze/thaw cycles did not significantly impact results.

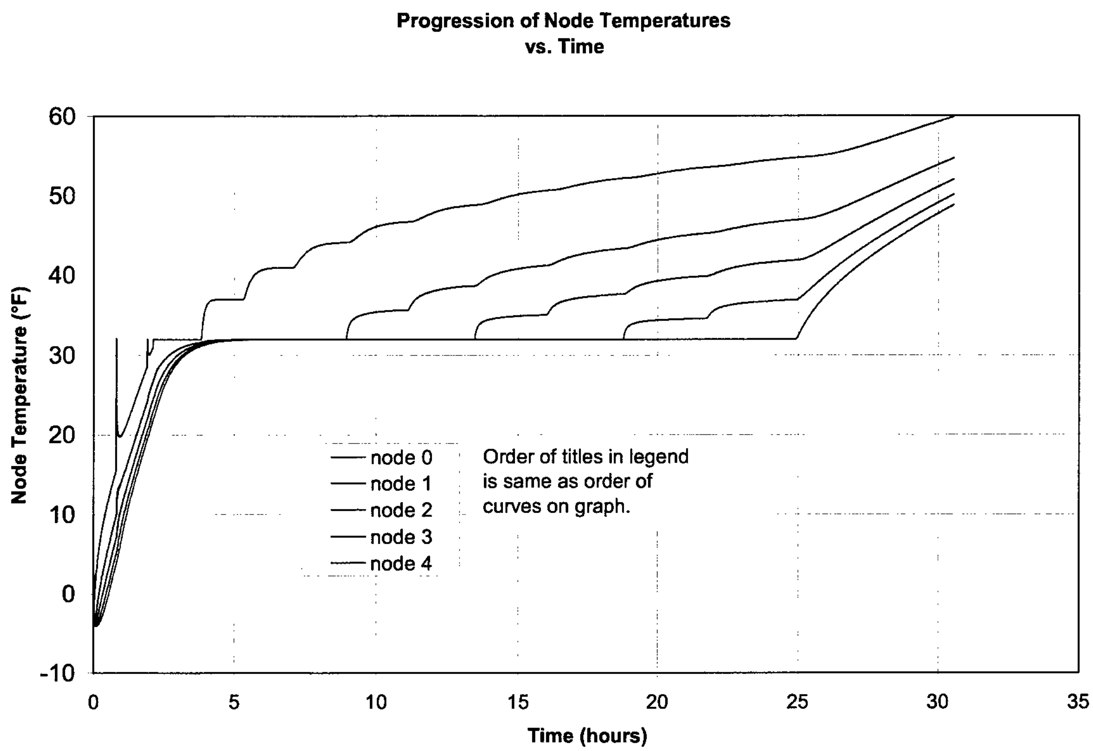

Figure 4. Results of the Numerical Program for Thawing of Beef Patties, Ambient Temperature 72°F, Outside Heat Transfer Coefficient = 10 W/m^{2}K,

Locations of Nodes: Node 0 – outside of the plastic cover, Node 1 – 12 mm inside, Node 2 – 37 mm inside, Node 3 – 62 mm inside, Node 4 – 87 mm inside

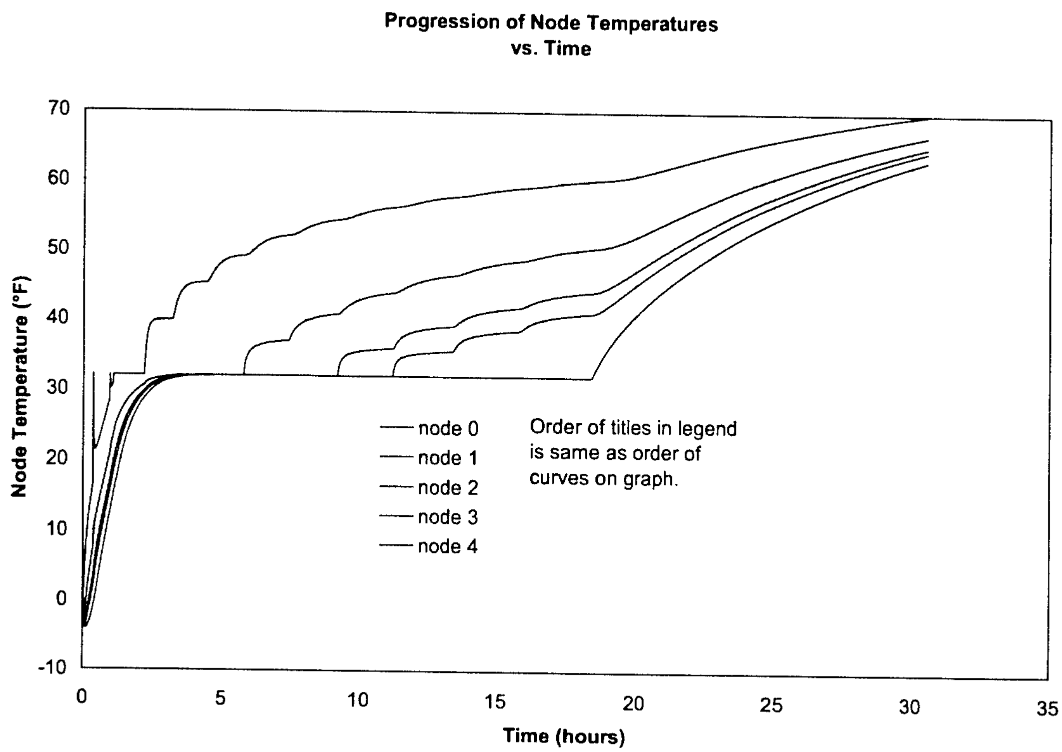

Figure 5. Results of the Numerical Program for Thawing of Beef Patties, Ambient Temperature 72°F, Outside Heat Transfer Coefficient = 17 W/m^{2}K,

Locations of Nodes: Node 0 – outside of the plastic cover, Node 1 – 12 mm inside, Node 2 – 37 mm inside, Node 3 – 62 mm inside, Node 4 – 87 mm inside

Bumpiness of the curves is caused by the finite size of the element and time step used in the model. They can be eliminated by using larger number of nodes in the model, however the computational time then becomes unacceptably long.

Table 2. Predicted and Experimental Melting Times

Node	Melting Time (hours) for		
	h=10*	h=17*	Experimental
0	3.84	2.16	2.4
1	8.88	5.76	4
2	13.44	9.12	8.5
3	18.72	13.44	11.5
4	24.96	18.24	14.5

*h units are W/m^{2}K

4. Continued Experimentation

4.1 Procedures

Authentic samples of packaged beef, chicken, and sausage from the UGR-A were obtained. For these trials, entire cases of meat were used, as received except for the installation of thermocouples. The steak weighed 22 lbs, the chicken weighted 10 lbs, and the sausage, 10 lbs. Each box contained the product packed in sealed plastic bags. The sausage (**Figure 6**) and chicken were loosely packed. The chicken portions were single breasts and the sausage was in individual links. The steaks were single fillets and tightly packed; sealed in a vacuum, they formed a solid block.

As illustrated in **Figure 7** and **Figure 8,** the cases were instrumented by attaching thermocouples at the following key locations:

- Air stream
- Outside of cardboard case
- Between cardboard case and plastic wrap
- On surface of meat near center of box
- Within a center piece of meat at uniform distance of approximately 1 inch (25 mm)

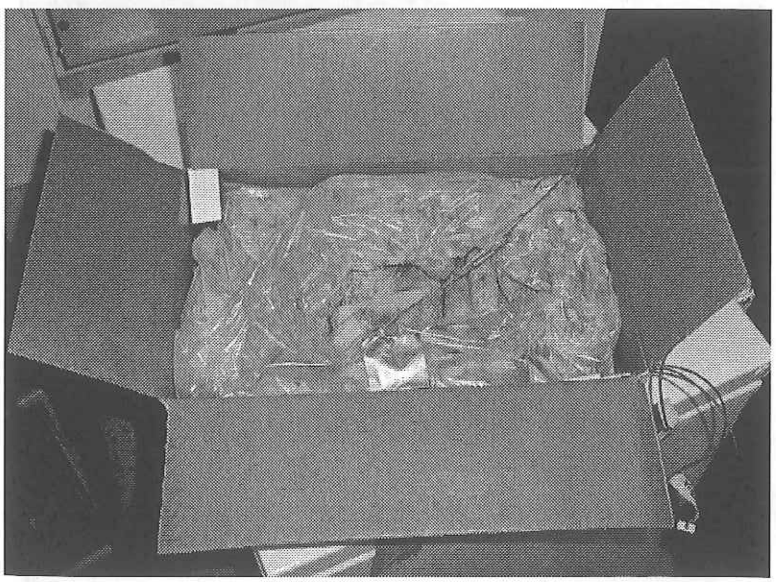

Figure 6. Loosely Packaged Sausage Links

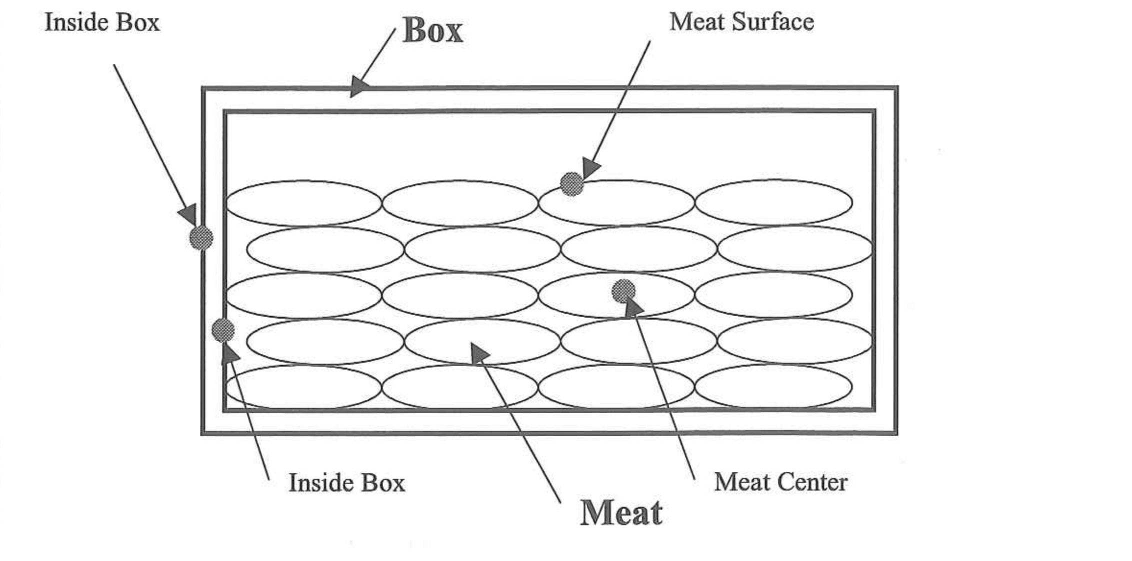

Figure 7. Thermocouple Locations

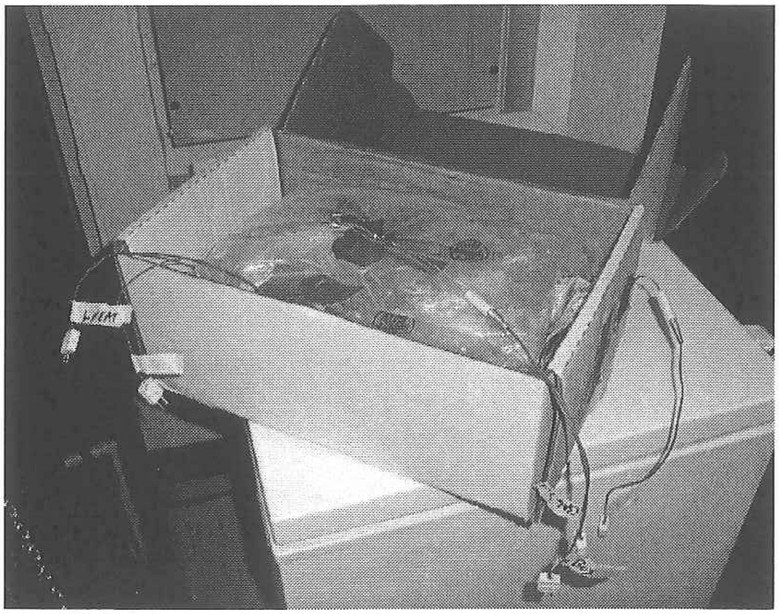

Figure 8. Vacuum-Packed Steak w/Thermocouples

The exterior and interior thermocouples were all positioned at the centerline of the box. The meat surface thermocouple was located near the "inside box" thermocouple but on the surface of the meat beneath the plastic. The meat thermocouple was located inside a piece of meat at the center of the product group.

The thermocouples were wired to a computer equipped with data acquisition hardware and LabVIEW® instrument management and data logging software. Data was collected at one second intervals. Except for ambient temperature data, the results are presented as 5 minute averages to make the illustrations clearer, and the charts more manageable.

Each product was run through the various experiments in its original packaging. Every effort was made to develop the experimental setup such that the thawing process would represent realistic conditions. One trial was run for each condition.

As recommended by military doctrine, the product was then stored in a freezer at (-4 to -8°F). This is Step 1 of **Figure 9**. After 24 hours an entire case will be at uniform temperature and it can be removed and placed on a wooden table in front of a fan for Step 2. The fan speed can be varied to provide air movement from zero (representing quiescent air) to approximately 5 miles per hour (representing gentle breeze). For these experiments the air velocity used in the forced convection experiments was fixed at 400 ft/min ± 10 ft/min.

Three environments were used to determine the effect on the thawing history. The first, is within a freezer set to 34.5±2.5°F. The second and third were at ambient temperatures maintained between 72°F (22°C) to 79°F (26°C) with a mode of 75°F (24°C); one was subjected to forced convection, and the other with natural convection only.

The product is considered thawed when the thermocouple in the product center passes through the 32°F (0°C) latent transformation plateau.

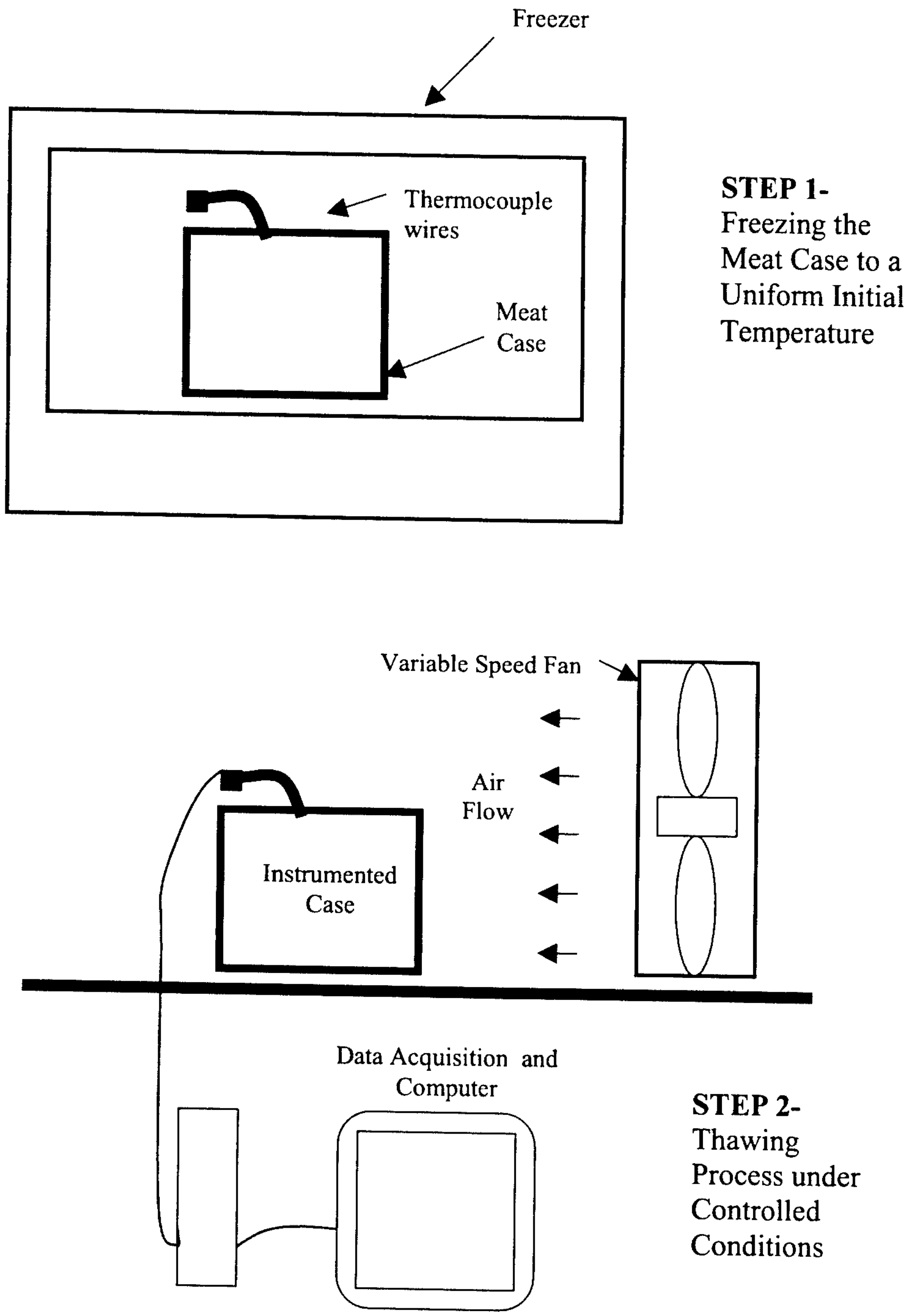

Figure 9. Details of Steps Followed During Thawing Experiments

4.2 Results

4.2.1 Thawing of Meat at Ambient Temperature with no Additional Provisions

Results of thawing at ambient temperatures with no applied breeze are shown in **Figure 10** and **Figure 11**. The chicken thawed in 92 minutes and the sausage was thawed after 73 minutes. The chicken breasts were only 3/8ths of an inch thick, and loosely packaged. A steak trial for these conditions was attempted, but results could not be reported for two reasons. The data acquisition system could not run for more than 30 hours and the cycling of the room ambient temperature was excessive during this long period.

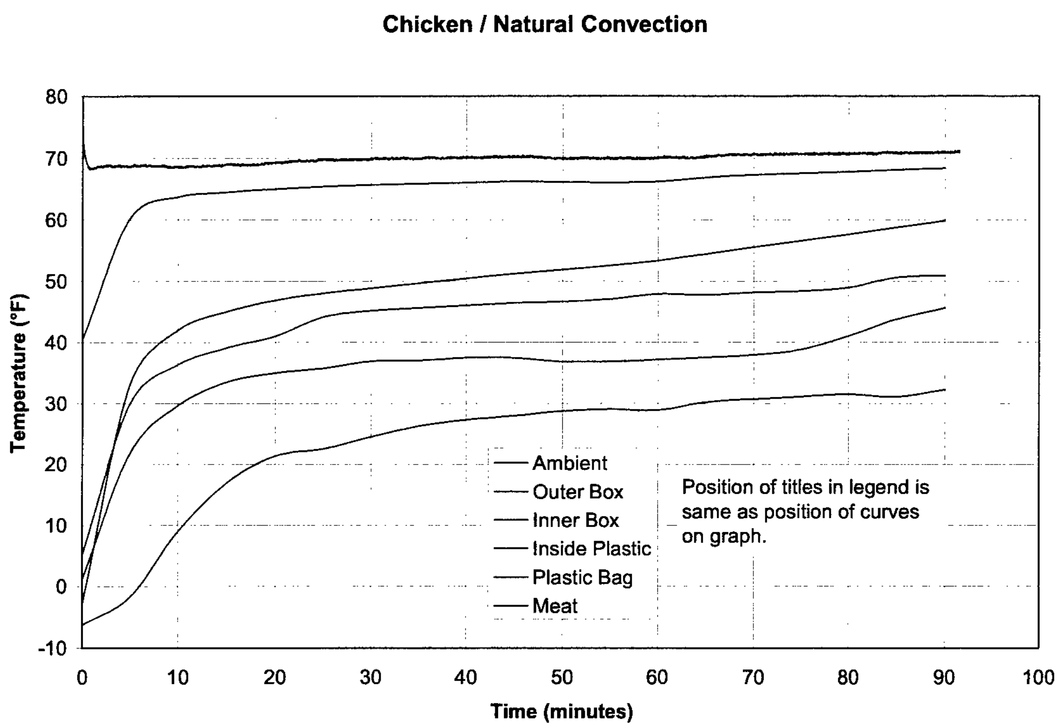

Figure 10. Chicken Thawed at Ambient Temperature with no Additional Provisions

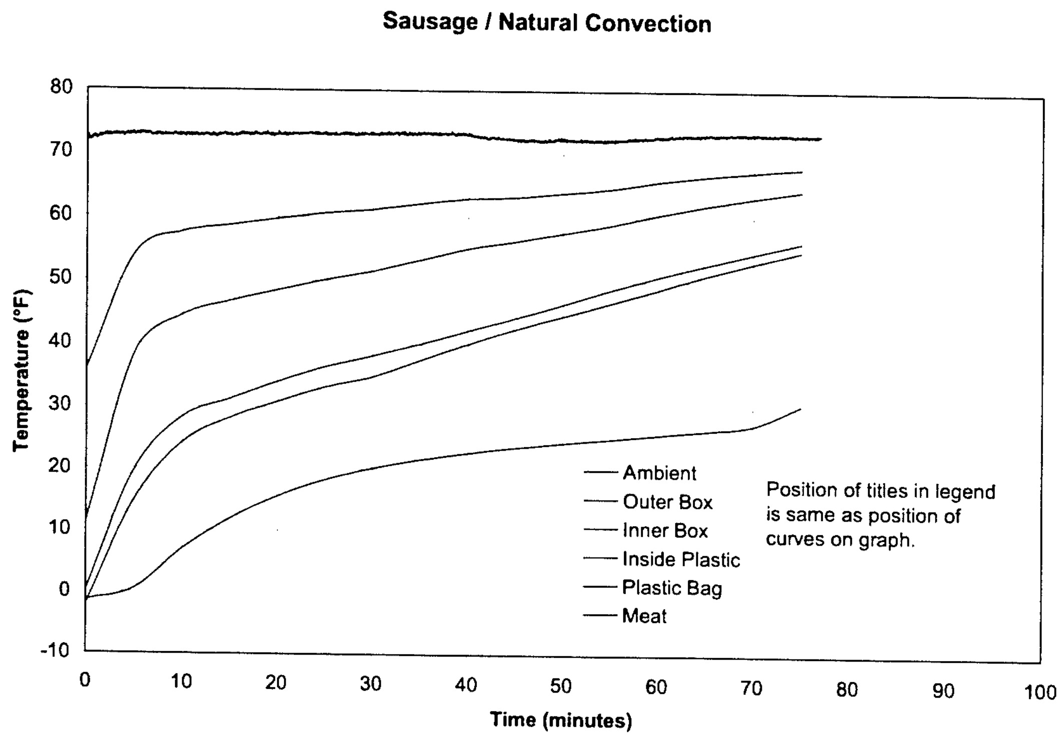

Figure 11. Sausage Thawed at Ambient Temperature with no Additional Provisions

4.2.2 Thawing of Meat in Controlled Cold Temperature Environment

The UGR-A meat products were transferred from a sub-zero freezer to a test refrigerator (**Figure 12**). The chicken was tested at 45°F, and the steak and sausage were tested at 35°F.

Figure 13, **Figure 14**, and **Figure 15** show the thawing history for the chicken, beef, and sausage respectively.

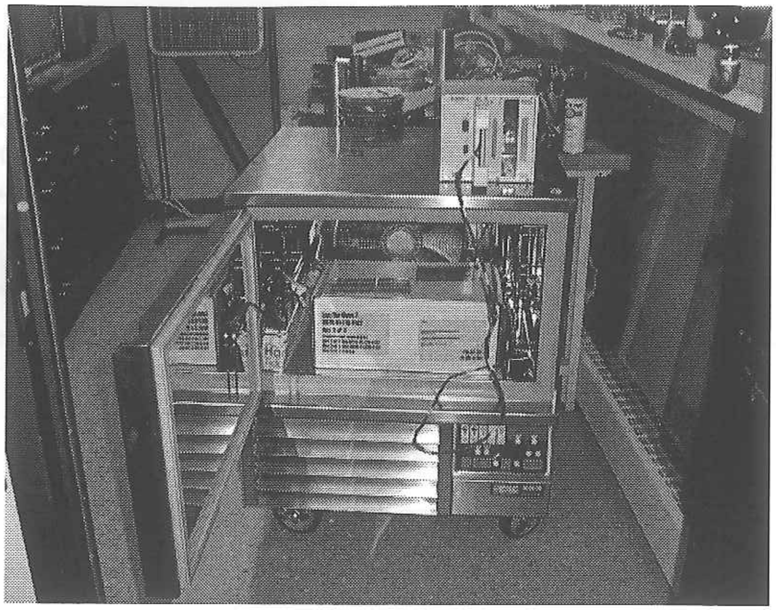

Figure 12. Test Refrigerator w/Case of Meat
(note data acquisition system on top)

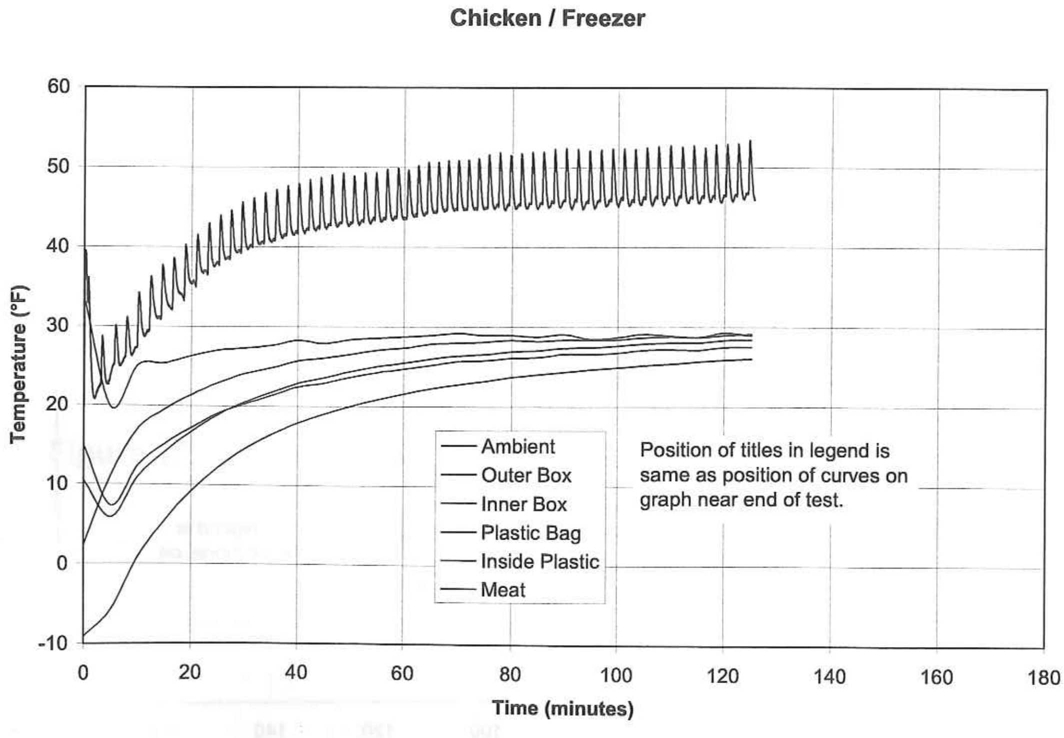

Figure 13. Thawing Chicken in 45°F Environment

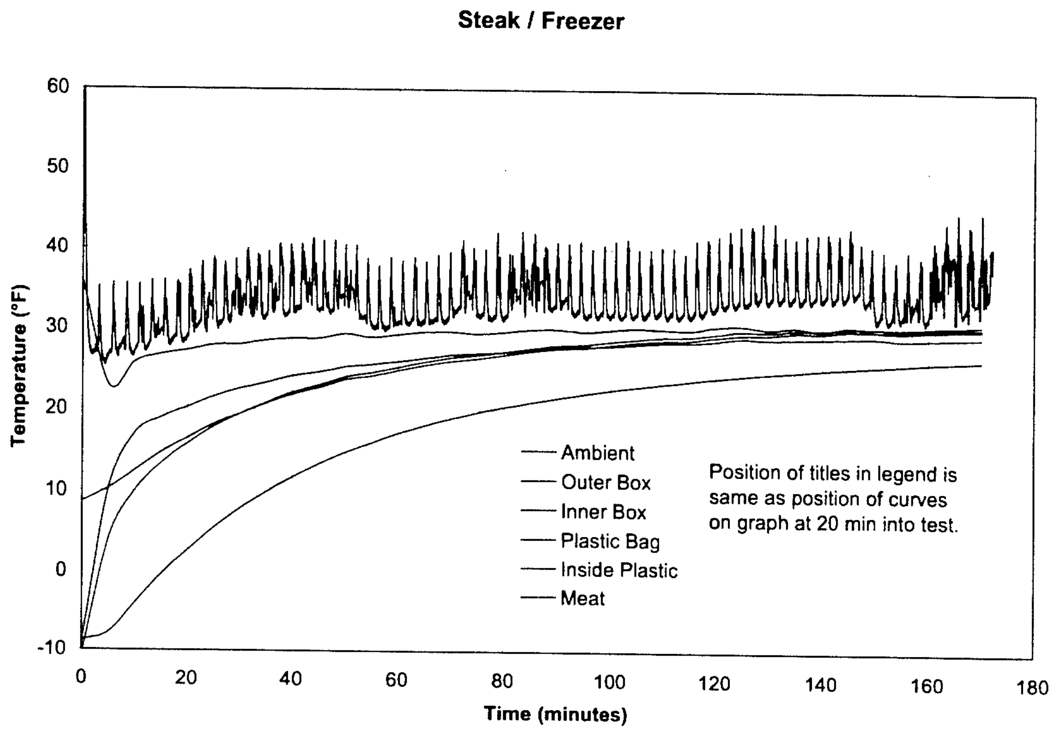

Figure 14. Thawing Steak in 35°F Environment

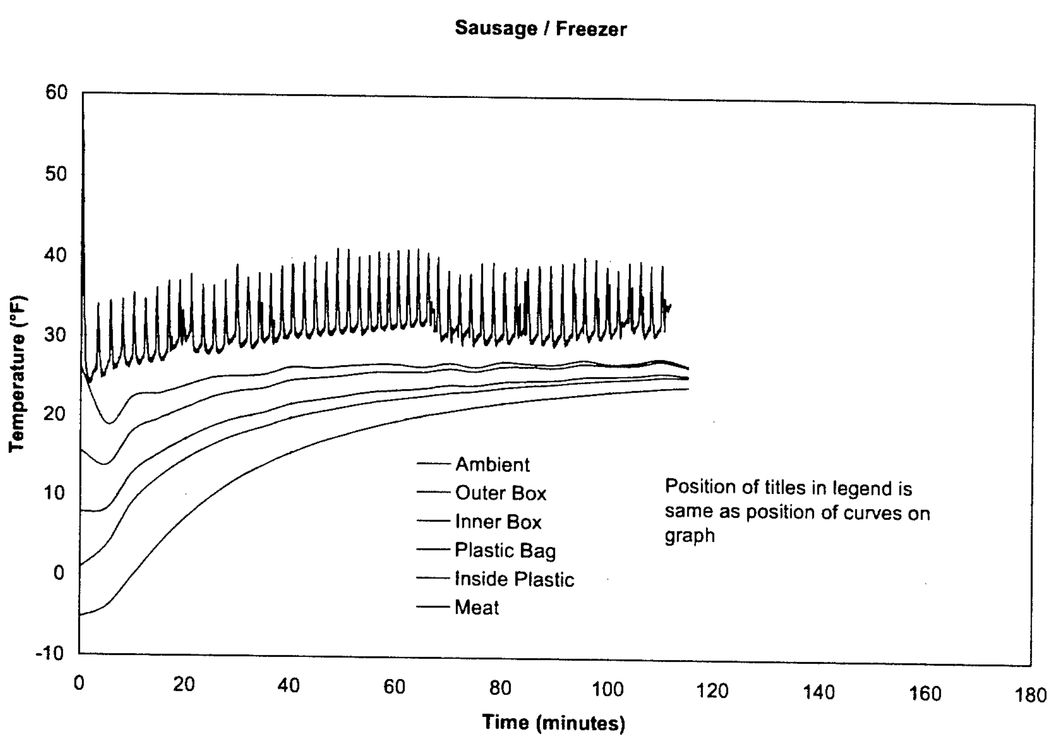

Figure 15. Thawing Sausage in 35°F Environment

After two hours, the center temperature of the chicken had not reached 30°F (-1°C). It plateaued just below that value. For the steak (after 2.5 hours) and sausage (1.75 hours), the center temperature did not breach 25°F (-4°C). The following tests report on the complete thawing process so it can be seen where the product transitions from latent to sensible heat transfer.

4.2.3 Thawing of Meat at Ambient Temperatures with Forced Convection

The cases were refrozen and then subjected to a forced convection environment. The air velocity was kept constant at all times. **Figure 16, Figure 17**, and **Figure 18** show the thawing history for the chicken, beef, and sausage respectively. The completion of the thawing process is defined as the point at which the meat enters sensible heat transfer. On the graph this corresponds to the point where the temperature begins to climb dramatically.

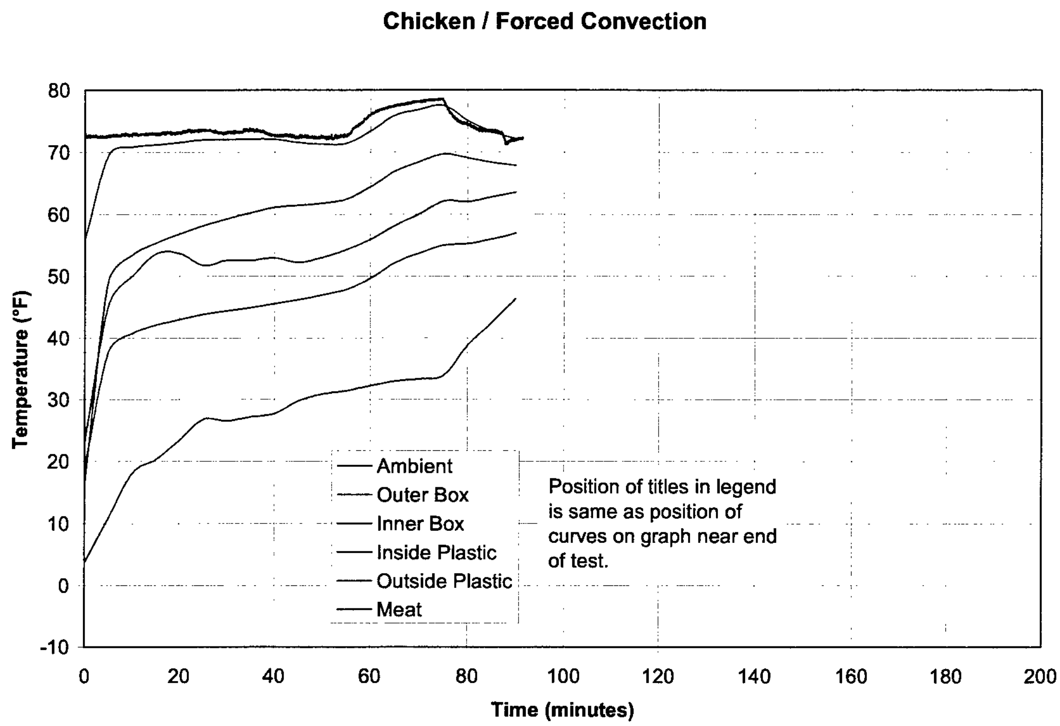

Figure 16. Chicken Thawed at Room Temperature w/Convection

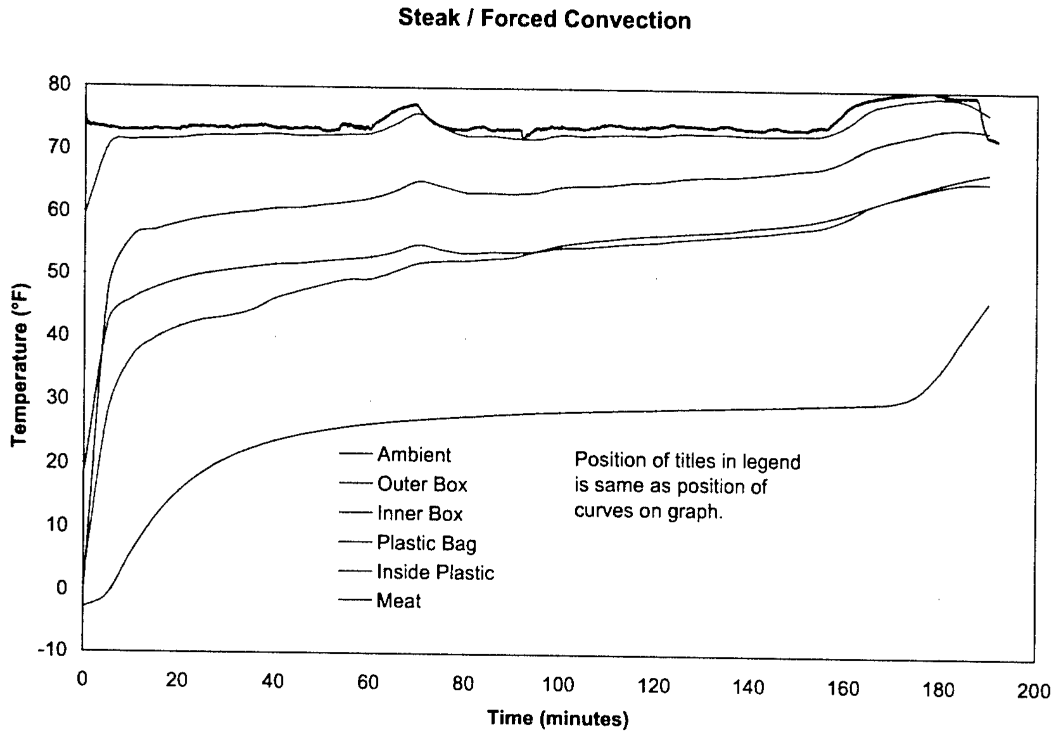

Figure 17. Steak Thawed at Room Temperature w/Convection

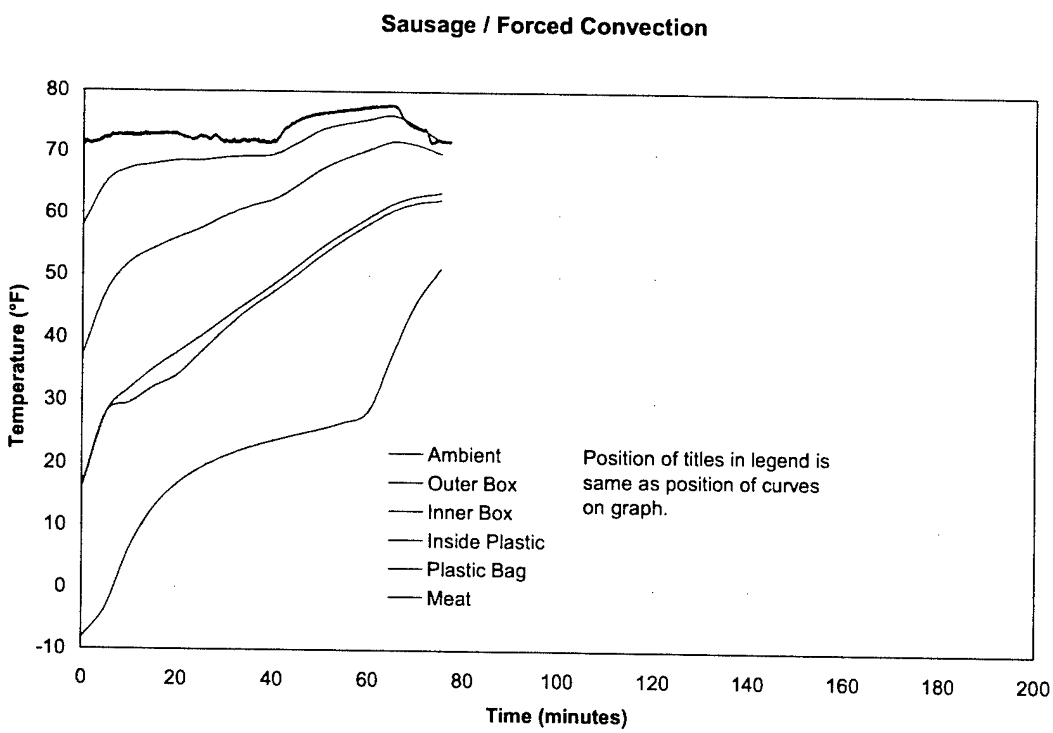

Figure 18. Sausage Thawed at Room Temperature w/Convection

The chicken thawed in 55 minutes. The sausage thawed in 60 minutes. The steak took the longest and thawed at 175 minutes due to its mass and tighter packing configuration. The chicken, on the other hand, is less than a half-inch thick. Furthermore, the loosely packed chicken and sausages have air gaps amongst the individual pieces. This aids air circulation and provides a better mechanism for heat transfer from outside surfaces to the interior.

A result summary for each condition is given in **Table 3**. Thawing times in the 35°F refrigerator were not carried to their completion as times exceeded 180 minutes.

Table 3. Duration Summary

Product	Thawing Time (minutes)		
	35°F Refrigerator	Natural Convection	Forced Convection
Chicken	>180	92	55
Steak	>180	N/A	175
Sausage	>180	73	60

Note: forced convection was at approx. 73°F

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5. Conclusions

These preliminary experiments clearly demonstrate the inadequacy of current methods used to thaw meat under field conditions. The significant amount of time meat surfaces reside above the safe limit of 41°F renders them susceptible to infestations of microorganisms.

The two primary constraints on the process, temperature and time, are difficult to balance simply by changing the ambient temperature. It was found that thawing in a 45°F environment is sufficient to satisfy the first constraint, however the small ΔT inhibits heat transfer to an extent it results in unacceptably long thawing times beyond the desired 16-18 hours.

However, there are other variables that may be safely manipulated. The heat transfer coefficient may be boosted by increasing convection across the product without increasing ambient temperatures. Furthermore, the most even thawing and fastest rates were found in loosely packaged meat, suggesting that air flow among a product provides some advantage.

This study also showed how numerical modeling can be effectively utilized to simulate the thawing process. When coupled with experimental data, it provides an effective way to obtain, for instance, heat transfer coefficients at different operating configurations.

Recommendations to maintain mandatory and optimal thawing conditions are as follows:

1. Meat surface temperatures should never exceed 40°F. The difference between thawing times at 35°F vs. 45°F was significant. Therefore under no circumstances should thawing be performed below 41°F. Since the doctrine allows 45°F, it is recommended such be allowed.
2. The above can be satisfied through careful selection of ambient temperature and air velocity. If high air temperatures are necessary, a low h value is recommended. High h values are necessary when ambient temperatures are low. The balance will shift as the meat thaws. Best results may be achieved by beginning with a large ΔT at the beginning of thawing, decreasing it as thawing progresses.
3. It is recommended meat be loosely packed to allow air surrounding the meat an opportunity to distribute heat. If products are not packaged this way, significant advantage can be gained by breaking it into as many portions as possible.

Simplistically, a technique for controlling meat temperatures, is to rely on the packaging in high ambient temperatures, and strip it away if conditions permit. However a thawing system with closely controlled temperature in the vicinity on 45°F, coupled with an air moving device, such as fan, would provide much greater control. Ultimately, it is not enough only to achieve optimal conditions, but then to maintain them over a range of environmental conditions, and as the relationship between the product and its environment changes. Therefore, advanced strategies are needed. Determination of these was beyond the scope of this project, and while the results of this study can serve as a guide towards choosing a thawing scheme, more specifics must be carefully examined. The following recommendations are offered for future work. They are broken down into two categories, mathematical modeling and experimental work.

Mathematical Modeling

1. Beyond the one dimensional analysis performed in this study, future models might include an entire case of meat, and then an entire UGR-A pallet. Naturally, pre-analysis of concept systems is very important prior to the development process.
2. A market survey performed by Natick Laboratories showed that the use of phase change material enclosures is a popularly suggested solution to this thawing problem. Phase change mixtures designed to hold interior conditions at 45°F while buffering high exterior heat loads might be feasible, however, little investigation has been done to prove the actual efficacy. Such a system might warrant first investigation.
3. The effect of all operating variables, that is, their practical limits, influence, trade-offs, and mutual relationships should be determined. Even the two primary variables, temperature and air velocity, are not exhaustively understood at this point. .

Experimental

1. Actual performance will vary depending on product-based variables such as packaging, salt, water and fat content. Since there really is no set group of items representative of what is in the field, it might be useful as part of the project to obtain a variety of products at a supermarket. Differently treated meat products might be evaluated with these variables in mind. This might also be the most sanitary, economic, and generally practical course of action versus procurement and shipping frozen UGR-A meat from a Defense Supply Center.
2. The use of fins and other means for heat transfer could be evaluated.
3. Quantification of packing density and its effects will prove valuable.

This document reports research undertaken through the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-02/021 in a series of reports approved for publication.

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APPENDIX

Appendix - Excerpts Referenced on the Proper Handling and Tempering of Potentially Hazardous Foods

Appendix - Excerpts on the Proper Handling and Tempering of Potentially Hazardous Foods

FM 10-23

- Frozen items, including meat, should be frozen solid when received.
- If they are thawed, they must be used right away (if approved by the veterinary food inspector), and should never be refrozen.
- Packages are checked on all sides for ice, which is a sign that they have been thawed and been refrozen.

TB-MED 530

- From section 2-21 - *Tempering Potentially Hazardous Frozen Foods (PFHs):*
  PHFs will be tempered or thawed only:

  1) In designated tempering units operated at an air temperature not to exceed 45°F (7°C); or;
  2) in general refrigeration units operated at an air temperature not to exceed 40°F (4°F); or;
  3) as part of the conventional cooking process; or;
  4) in a microwave oven, provided the food is immediately transferred to conventional cooking facilities as part of a continuous cooking process, or when the entire, uninterrupted cooking process takes place in the microwave oven; or
  5) under potable running water at a water temperature of 70°F (21°C) or below. Water velocity will be sufficient to agitate and float off loose food particles into the overflow. When poultry is tempered in this manner, all surfaces of sinks, equipment, and utensils used will be sanitized immediately afterwards to minimize cross-contamination. Whenever practicable, frozen foods should be placed in a sanitized pot or other container and the water allowed to overflow into the sink. This is the least preferred method for thawing or tempering frozen foods.

1999 Food Code

- From section 3-501.13 – *Thawing:*
  Except as specified in item (4) of this section, potentially hazardous food shall be thawed:

  1) Under refrigeration that maintains the food temperature at 5°C (41°F) or less, or at 7°C (45°F) or less as specified under 3-501.16(3); or,
  2) Completely submerged under running water:
     a) At a water temperature of 21°C (70°F) or below; or,
     b) With sufficient water velocity to agitate and float off loose particles in an overflow; and,
     c) For a period of time that does not allow thawed portions of ready-to-eat food to rise above 5°C (41°F), or 7°C (45°F) as specified under q(3-501.16(3); or,
     d) For a period of time that does not allow thawed portions of a raw animal food requiring cooking as specified under q[3-40 1.11 (1) or (2) to be above 5°C

(41°F), or 7°C (45°F) as specified under 3-501.16(3), for more than 4 hours including:

i) The time the food is exposed to the running water and the time needed for preparation for cooking; or,
ii) The time it takes under refrigeration to lower the food temperature to 5°C (41°F) or 7°C (45'F) as specified under 3-501.16(3).

e) As part of a cooking process if the food that is frozen is:
   i) Cooked as specified under 13-401.1 l(1) or (2) or 4 3-401.12; or,
   ii) Thawed in a microwave oven and immediately transferred to conventional cooking equipment, with no interruption in the process; or
f) Using any procedure if a portion of frozen ready-to-eat food is thawed and prepared for immediate service in response to an individual consumer's order.